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The Cryogenian record in the southern Kingston Range, California: the thickest Death Valley succession in the hunt for a GSSP

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ABSTRACT

The Kingston Peak Formation of the Death Valley area, California, allows valuable insight into both regional Cordilleran stratigraphy and the number of glacial cycles preserved in the Cryogenian record. In the Kingston Range, the eponymous strata have been previously interpreted to record both Sturtian and Marinoan pan-glacial events. In the context of a search for a Global Boundary Stratotype Section and Point (GSSP) for the Cryogenian, we provide the first detailed description of the thickest diamictite-bearing interval in the western USA. Two clast-poor, muddy diamictite intervals within the succession- one at the base, and one near the top- have been used to support Sturtian and Marinoan events previously. However, new data from the southern part of the Kingston Range suggest that the upper diamictite interval is genetically related to underlying strata. The deposits are interpreted as glaciogenic debris flow deposits which probably represent the proximal tract of a subaqueous fan. Medial to distal portions of this fan are dominated by turbidites, which were transported down a consistent SE-oriented palaeoslope. Lowermost beds of the upper diamictite interval are intercalated with graded sandstones and sandy, matrix supported conglomerates. The graded beds (turbidites) and matrix-supported conglomerates (debrites) testify to a subaqueous setting, with the compositionally and texturally distinct diamictites indicating a glacial origin.

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1. Introduction

A major priority for Precambrian research is the establishment of a suitable and representative Global Boundary Stratotype Section and Point (GSSP) for the Cryogenian period (Shields-Zhou et al., 2016). Current thinking suggests that GSSPs should be chosen by physic-chemical markers, rather than having any biostratigraphic basis (Smith et al., 2015). In this context, we present a case study of the thickest hitherto published example of a Cryogenian diamictite succession in the Death Valley region, California, USA (**Fig. 1**). We consider the evolution of this succession in terms of the number of glacial cycles preserved by comparison to successions in neighbouring outcrop belts, and in terms of the "completeness" of its record. The succession of diamictite-bearing rocks of the Kingston Peak Formation described in this paper are 2.5 km thick, and represent the thickest known accumulations of Cryogenian glacially-related strata in the western USA. Prior to a recent study in the Silurian Hills, (approximately 30 km to the SW of the study area) where 1.4 km of diamictite-bearing strata were measured (Le Heron et al., 2017), it was thought that the thickest accumulation of Cryogenian diamictites cropped out in the Panamint Range immediately west of Death Valley (Miller, 1985; Prave et al., 1999). Indeed, prior to the present contribution, the thickest known accumulations in the western USA were reported from the Dutch Peak Formation in the Sheeprock Mountains of Utah (Christie-Blick et al., 1982). In general terms, owing to the likely duration of time over which these rocks accumulated (possibly 55 Ma: Rooney et al., 2015), it is probable that they record much lower accumulation rates (perhaps 4-15 times slower) than either Palaeozoic or Cenozoic glacial successions (Partin and Sadler, 2016).

The Kingston Peak Formation is of global significance as it is an exceptional archive for Cryogenian climate cycles. Ever since Hazzard (1933) recognised evidence for glacial deposition in the Kingston Peak Formation of the Death Valley area (then regarded as Cambrian in age), various attempts have been made to establish the significance of these deposits in a wider regional and ultimately global context. Miller (1985) argued for two phases of glaciation in strata of the Panamint Range immediately west of Death Valley, with basalts within the middle of the succession (Labotka et al., 1980) cited as archetypal evidence for two phases of Rodinian rift margin development (Prave, 1999). Prave (1999) provided an overview of the formation throughout the Death Valley area, using outcrops in the Panamint Range in particular to argue for a two-phased glaciation allied to two phases of continental rifting. The popular two-phased model was revived in Macdonald et al. (2013), who also argued that discrete phases of glaciation had produced discrete tectonostratigraphic units which could then be correlated across the US Cordillera as isochronous time markers. The earlier phase of glaciation was proposed to be Sturtian in age, whereas the later phase of glaciation was allied to the Marinoan glaciation of South Australia (Macdonald et al., 2013). Based on a very detailed investigation of the Silurian Hills, Le Heron et al. (2017) identified four main packages of glacial diamictite interbedded with slope-derived olistostrome material, hence casting doubt on the universal applicability of a two-fold glaciation, and raising questions about which study area, if any, should be regarded as a representative archive of the Cryogenian glacial record.

2. Previous work and context

Prave (1999) proposed a regional stratigraphy for the Kingston Peak Formation (KPF), which saw it divided into three ascending stratigraphic units (KP1-3). The lowermost of these (KP1) comprises monotonous siltstone and sandstone intercalations that are devoid of any evidence for a glacial influence and hence considered genetically unrelated to the overlying strata. KP2 comprises a laterally extensive diamictite unit (Prave, 1999). The overlying unit (KP3) was argued to represent a glacial retreat. Macdonald et al. (2013) adopted similar interpretations to Prave (1999), developing the idea that units KP2-KP3 represented the record of the Sturtian pan-glacial. These authors slightly misquoted both Wright (1954) and Prave (1999) to whom they attributed a new stratigraphic unit (KP4) at the top of the succession. However, whilst the origins of a fourfold stratigraphic subdivision can be traced to Wright's (1974) mapping of the southern Alexander Hills (Tecopa) area, the description of his units (pЄk1-pЄk4) do not closely match the descriptions in either Prave (1999) or Macdonald et al. (2013). Reference to this unit is also made multiple times in Mrofka and Kennedy (2011), who cite Wright (1974) as the primary source of this stratigraphic unit, and in Mahon et al. (2014a) as a small channel-like feature at the top of KP3. Interestingly, Petterson et al. (2011) do not refer to it in their summary paper of the western Death Valley stratigraphy. Nevertheless, some authors have considered diamictites at the top of the Kingston Peak (KP4) to have global age significance: Macdonald et al. (2013) attributed this unit to the Marinoan glaciation. In the absence of good syn-depositional age constraints for the Kingston Peak Formation (e.g. Vandyk et al., in review), it thus remains contentious whether diamictite units are of local, regional, or global significance.

Macdonald et al. (2013) "observed" KP4 in the Saddle Peak Hills area, which they considered to be laterally equivalent to the Wildrose Diamictite in the Panamint Range (c.f. Prave, 1999, who considered this equivalent to KP2/3). The crux of the issue is that there is no formally documented type section or type area for the KP4 stratigraphic unit, yet in spite of this, it has been argued that the unit could be used for correlation across the North American Cordillera: Macdonald et al. (2013) attributed it to the Marinoan glaciation. With Macdonald et al. (2013) proposing that the lowermost unit of the Kingston Peak Formation (KP1 sensu Prave, 1999) was genetically unrelated to glaciation, Le Heron et al. (2017) questioned the applicability of this regional scale stratigraphy for the Silurian Hills area, because at least four distinct diamictite-dominated intervals can be observed in 1.4 km of stratigraphy (rather than the two recognised by Macdonald et al., 2013: i.e. KP2 and KP4). Le Heron et al. (2017) thus raised the possibility that Cryogenian glaciation in the Death Valley area may have been diachronous from outcrop belt to outcrop belt. This is an uncomfortable proposal because it conflicts with the idea of using diamictites as time markers over wide areas. In their provenance study, Mahon et al. (2014b) were able to distinguish different detrital zircon suites for the Pahrump Group, and for the Kingston Peak Formation where sediment input from the north, south, west and east was proposed. A progressive unroofing process was proposed, but the resolution of the published data do not enable the idea of a major break in time (i.e. major unconformity) between KP3 and KP4 to be substantiated. This idea awaits further data and further research.

Noting the problems above, we have two objectives, namely (i) to provide the first complete description of the thickest diamictite-bearing interval in the Death Valley area (S Kingston Range) and (ii) to propose new interpretations and palaeogeographic context for the diamictites. Building on recent work which focused on a limited interval of dropstone-bearing strata (Le Heron and Busfield, 2016), the new data in this paper are extremely important for evaluating regional correlations and evaluating temporal changes in Cryogenian glacial environments. Furthermore, the descriptions and interpretations are vital in providing (i) new data on a candidate region for placing a Cryogenian GSSP and (ii) properly evaluating the origins of the diamictites, and (iii) using sedimentological and stratigraphic relationships to consider the regional vs global significance of glacial cycles within the succession.

The tectonostratigraphic framework of Macdonald et al. (2013) was proposed on the basis of mapping work in the Kingston Range and in the Saddle Peak Hills (**Fig. 1**). Both areas were mapped by students to enable a composite stratigraphic framework that refined the previous work of Prave (1999). Further west in the Panamint Range, more continuous succession of strata is preserved including a laterally extensive limestone interval interpreted as a possible cap carbonate (the Sourdough Limestone) at the top of the interpreted Sturtian succession (Prave, 1999). However, detailed sedimentological investigation in that area is made all the more difficult as a result of the high grade (amphibolite) metamorphic overprint (Petterson et al., 2011). In our study area, the southern Kingston Range, the upper part of the KPF is truncated, at a very low angle, by the Noonday Dolomite. This dolomite unit contains a stable C isotope signature comparable to that of post-Marinoan cap carbonates (Prave, 1999; Macdonald et al., 2013). Whilst detailed studies of the Noonday Formation in the southern Kingston Range have yet to be done, recent work in the Saddle Peak Hills area by Creveling et al. (2016) established a full carbonate platform facies model. In that study, a basal unit with dololaminites was found to be typical,with tube-like structures once thought to be stromatolitic and now interpreted as gas-escape structures (Creveling et al., 2016) are recognised.

3. The southern Kingston Range succession

3.1 Introduction

The southern Kingston Range, which was first mapped by Calzia et al. (1987), exposes the geographically widest outcrop belt of Kingston Peak Formation (KPF) strata in the range and also the thickest strata (**Fig. 1**). Dip angles are typically greatest nearest to the Kingston Range granite intrusion at the western margin of the outcrop belt. In the Kingston Range, the Beck Spring Dolomite forms the basal Pahrump Group outcrop, overlain by a recessive unit comprising siltstone-sandstone intercalations interpreted as the lowermost, non-glacial strata of the KPF (KP1 of Prave, 1999). A poorly exposed example of the diamictite facies association of Le Heron et al. (2014), traditionally interpreted as unit KP2 (Prave, 1999; Macdonald et al., 2013), crops out above. This basal diamictite can be followed along strike and it is very well exposed 7 km further north, where it is intercalated with dropstone-bearing strata (Le Heron et al., 2014). This is overlain by the megaclast facies association, interpreted as an olistostrome, containing up to 700 m-scale blocks of the Beck Spring Dolomite.

3.2 Methodology

Over 6 weeks from 2014-2015, we measured a 2.5 km thick composite section (Fig. 2) of the KPF in the southern Kingston Range. This is the thickest KPF section in the entire Death Valley region. In this area, the following general stratigraphic summary can be made. The basal (KP2: Prave, 1999) diamictite is overlain by a thick, chaotically organised olistostrome complex. This in turn is capped by better organised graded conglomerate and sandstone beds that were briefly described and interpreted by Le Heron and Busfield (2016). These in turn pass upwards into a hitherto undescribed, but very well exposed, diamictite that is intercalated with graded conglomerate, sandstone and mudstone (**Fig. 2**). Our study used both mapping (basal diamictite and olistostrome complex), and logging at dm-scale resolution (supra-olistostrome complex) to derive the 2.5 km thickness (the olistostrome contains no definate *in situ* bedding planes). Previously, Mrofka and Kennedy (2011) reported that the succession was 3.2 km thick in this area (see their Figure 40.2 “Horsethief Mine section”). There estimation is ~0.7 km thicker than ours, possibly because rotated sandstone beds within the olistostrome were used for trigonometric calculations to determine true thickness of this unit.

In this paper, we build on the sedimentological template developed for other outcrop belts of the KPF by Le Heron et al. (2014), Le Heron and Busfield (2016) and Busfield and Le Heron (2016). These studies emphasise the co-genetic development of turbidites and ice-contact diamictites (Busfield and Le Heron, 2016). These studies established a suite of *facies associations* reflecting the dominant signature of gravity flows, with the full spectrum of debrites to low density turbidites recognised. Two of these deserve special emphasis: (i) a megaclast facies association (interpreted as km-scale blocks emplaced as part of an olistostrome) and (v) a diamictite facies association (interpreted as a series of glaciogenic debris flows, i.e. material reworked by gravity flows that is ultimately of glacial origin). The Kingston Range is viewed as a proglacial basin (Le Heron et al., 2014): it lacks glacitectonized deposits that are locally represented in Sperry Wash some 50 km to the east (Busfield and Le Heron 2016). Rather than focus on the sedimentological minutiae, the present manuscript is directed at considering the stratigraphic significance of diamictites in this important section.

3.3 Olistostrome complex: description

The metabasite suite comprises blue-green weathering crystalline rocks with intercalated sedimentary rocks. Both volcanic ash (Calzia et al., 1987) and fragments of diabase from the Crystal Springs Formation (Calzia et al., 2000) have been reported from the KPF previously: we discovered a 350 m thick diabase body (**Fig. 2**). A panoramic perspective (**Fig. 3**) highlights the internal heterogeneity of the olistostrome complex (**Fig. 3**), which includes large blocks of carbonate and arkose. The olistostrome complex commences with a single block of dolostone (**Fig. 2**, **Fig. 3**) which has intensely boudinaged (**Fig. 4 A**) and folded (**Fig. 4 B**) a mixed carbonate-siliciclastic interval beneath it. Solitary blocks of diamictite are encased within the olistostrome complex, and these can be demonstrated to be allochthonous on account of their locally oversteepened dips.

Outcrops typically include bulbous masses of material that are devoid of any internal fabric or foliation (**Fig. 4 C**). Elsewhere, xenoliths of sandstone and dolostone (**Fig. 4 D**) are observed. These are typically highly irregular in outline and exhibit baked margins. Elsewhere, ovoid “clast” and groundmass relationships are only faintly recognisable in the metabasite (**Fig. 4 E**). Petrographic analysis reveals extensive chloritization and alteration of the protolith, with chlorite laths possibly pseudomorphing feldspar (**Fig. 4 F**). At the outcrop scale, the metabasite rocks are intercalated with both normally and inversely graded siliciclastic sedimentary rocks that are essentially identical to those in the supra-olistostrome strata. The contact between the metabasite and the normally graded sedimentary rocks is concordant and devoid of a baked margin. Unidirectional ripple marks (**Fig. 4H**) are recorded on the upper surface of normally-graded sandstones.

3.4 Olistostrome complex: interpretation

The occurrence of an olistostrome, originally mapped in the Kingston Range as a “megabreccia”, has long been known (Hewett, 1956). The present study area was explored in terms of its resource potential by Calzia et al. (1987), noting the occurrence of iron accumulations both as sedimentary units within the KPF, and as skarns in contact with the Kingston Peak granite. These authors did not discuss the presence of metabasites within the olistostrome complex. Elsewhere in the Kingston Range (in the Excelsior Mine area, ~12 km NW of our study area) a 1.08 Ga diabase intrudes the Crystal Spring Formation (Heaman and Grotzinger, 1992). There are two possibilities: (i) extrusion of lava flows during rifting followed by downslope mobilisation and incorporation into the olistostrome (e.g. in the Moni

Mélange, Cyprus: Robertson, 1977) or (ii) that the metabasites are simply remobilised fragments of the Crystal Spring Formation diabase. The latter interpretation is supported on the basis of U-Pb dates obtained from apatites (Vandyk et al., in review). The occurrence of both normally and inversely graded sedimentary rocks together is noteworthy, because these facies (interpreted as turbidites and debrites respectively) have closely comparable counterparts in the supra-olistostrome succession as we shall discuss below.

3.5 Supra-olistostrome strata: description

The succession immediately above the olistostrome was described by Le Heron and Busfield (2016). That paper documented a well exposed interval of approximately 187 m thick, which was investigated in spring 2014. Subsequently, a 2015 field season included the discovery of excellent, complete sections above the olistostrome to be documented through the entirety of the uppermost KPF to the contact with the overlying Noonday Dolomite: an additional 430 m of superbly exposed strata allowing us to include a composite, though almost continuous, high resolution section through 617 m of stratigraphy (**Fig. 5**). The lowermost 180 m or so of supra-olistostrome strata is dominated by alternating packages of interbedded heterolithic and lonestone-bearing facies associations, punctuated at intervals by occurrences of the pebble to boulder conglomerate association. Le Heron and Busfield (2016) interpreted the interbedded heterolithic facies association - which comprises intercalated normally graded beds, ripple cross-laminated intervals and clast-free mudrocks - as low-density turbidites. A similar interpretation for the lonestone-bearing facies association was proposed, with the key difference lying in the occurrence of abundant dropstones. Hence, a strong overprint of ice-rafting was proposed, and hence evidence for a glacial influence, in some intervals of the supra-olistostrome strata. The pebble to boulder-conglomerate facies association, by comparison, was interpreted as high-density turbidite deposits. No diamictites were described by Le Heron and Busfield (2016).

Appraising the entirety of the supra-olistostrome succession (**Fig. 5**), three first-order generalisations can be made: (1) the occurrence of thicker, progressively more amalgamated packages (~50 m or so) of the pebble to boulder conglomerate association upsection, (2) the intercalation of the interbedded heterolithic facies association between the conglomerates and (3) the appearance of muddy diamictites in the succession, initially as isolated beds at 180 m and 198 m, and forming repeated, progressively thicker (~30 m) beds/units over an interval of almost 100 m (between 509 m and 608 m on the measured section **Fig. 5**) at the very top of the KPF. In this paper, we refer to this interval as the upper diamictite. Establishing the correct stratigraphic context of the upper diamictite, and its relationship to underlying deposits, is vital seeing that it is viewed as the Cordilleran equivalent of the Marinoan glacial record (Macdonald et al., 2013). The diamictite beds show an interesting relationship with other siliciclastic deposits. For example, a clear coarsening-up motif can be identified from 509-547 m; the lower part of this section comprises coarsening upward diamictite (showing both increase in clast size and matrix composition tending toward more sandy) whereas the upper part comprises stacked, normally graded granule-pebble and cobble-boulder conglomerates (**Fig. 5**). In other occurrences beneath the Noonday dolomite, abundant dropstones are recorded within stratified diamictites, particularly in the interval at 582-588 m and directly below the Noonday (604-607 m). Normally graded conglomerates and sandstones account for any non-diamictite strata in the upper part of the KPF. Palaeocurrent data (shown next to the log in position and as summary rose diagrams) indicate a uniform SE palaeoslope throughout deposition, with very few exceptions. Thus, there is no apparent difference in flow direction recorded below or within the upper diamictite interval.

Owing to its stratigraphic position almost 2 km above the basal diamictite (KP2 of Prave, 1999: **Fig. 2**), it is important to consider the origin of the upper diamictite separately. Whilst sedimentary evidence for a glaciogenic origin for the basal diamictite was well established in the northern part of the Kingston Range (intercalated mudrocks bear dropstones: Le Heron et al., 2014), the sedimentological case for a glacial origin in the upper diamictite (KP4 of Prave, 1999) remains to be fully established, although it should be noted that Mrofka (2010) recovered some excellent striated pebbles from this level in the Jupiter Mine area, some 8 km north. The gradational relationship between diamictite lithofacies and normally graded sandstone beds in the upper diamictite interval is apparent (**Fig. 6 A, B**). Cobble-sized dropstones occur within stratified diamictites (**Fig. 6 B**), and some of these exhibit striated surfaces (**Fig. 6 C**). Dropstones are abundant at the pebble-scale and rather than deflect / downwarp the diamictite lamination, the stones puncture into underlying laminae and are draped by undeformed laminae (**Fig. 6 D, E**). The dropstones occur at intervals throughout the upper diamictite, including immediately below the contact with the Noonday Dolomite (**Fig. 6 F**).

The upper diamictite interval contains numerous examples of asymmetric rippled surfaces (**Fig. 7 A**), pointing to unidirectional flow into the basin. It also contains excellent examples of normally graded beds (**Fig. 7 B, C**) which are compositionally and texturally identical to those described previously from the lower levels of the supra-olistostrome strata (Le Heron and Busfield, 2016) and indeed to those contained within the olistostrome complex (see **Fig. 4** G). Diamictite beds show upward transitions into normally-graded conglomerate (**Fig. 7 D**); in other cases stacked, intervals dominated by normally-graded beds are punctuated by occasional diamictite beds (**Fig. 7 E**). Unidirectional ripple cross-lamination, almost exclusively indicating a SE-palaeoflow, occurs at the top of many normally-graded beds. The diamictites vary widely in terms of colour (including both reddish-brown (**Fig. 8 A**) and green (**Fig. 8 B**) varieties), in terms of the number of clasts, and in terms of clast composition. Clasts include psammite (**Fig. 8 D**), dolostone (**Fig. 8 E**), metabasite (**Fig. 8 E, F**), oncolitic dolostone (**Fig. 8 G**), stromatolitic dolostone, sandstone and quartzite (**Fig. 8** H), together with schists.

3.6 Supra-olistostrome strata: interpretation

The supra-olistostrome package is interpreted to record the progradation of a major subaqueous fan complex directly comparable to that in the Sperry Wash area some 50 km to the west (Busfield and Le Heron, 2016). The overall coarsening upward trend is compatible with progressive infill of the basin, with the abundant stacked fining up motifs both in the pebble to boulder conglomerate and interbedded heterolithic facies associations interpreted as a spectrum of high- to low-density turbidites. The diamictite facies association, which occurs at an almost identical stratigraphic level to that at Sperry Wash (Busfield and Le Heron, 2016), is interpreted as a combination of primary and secondary glacial deposition, including both primary rain-out sedimentation, and downslope reworking and modification of the glacial debris. The clear vertical transitions that can be observed, at an outcrop scale, between diamictite and sandstone (**Fig. 6 A**) or diamictite and conglomerate (**Fig. 7 D**) strongly imply a genetic (process) connection between these lithologies. The massive diamictites are interpreted as debrites, representing reworked equivalents of the stratified diamictites. A direct glacial influence for the stratified diamictites is implied by (i) the abundant dropstone textures within these facies and (ii) the striated surfaces of some clasts. The occurrence of a wide variety of extra-basinal clasts (igneous and metamorphic lithologies) within the diamictites is strongly suggestive of a wide provenance compatible with the re-advance of ice masses over the Southern Kingston Range.

The relationships between diamictites and associated facies have been poorly documented to date. In the southern Kingston Range, high quality exposure demonstrates the intercalation of diamictites, conglomerates (as noted above), and thin heterolithic intervals (**Fig. 9**). In previous work (Le Heron et al., 2014), it was suggested that the Basal Diamictite of the KPF (i.e. those belonging to unit KP2 of Prave, 1999) (**Fig. 2**) represents mostly glaciogenic debris flow deposits, with some evidence for stratification testifying to waterlain deposition. For the upper diamictite, we propose a similar model, albeit with a small but important modification. As established above, a genetic connection between diamictites and conglomerates is indicated by the transitional nature of boundaries, some of which are diffuse (e.g. **Fig. 7 D**). Stratification is also represented in these diamictites, but importantly, we recognise both striated clasts (**Fig. 6 C**) and the piercement of stratification by outsized clasts at some parts of the diamictite exposure (**Fig. 6 E**). These latter observations demonstrate that the clasts represent ice-rafted debris (Le Heron, 2015).

4. Lateral extent and significance of diamictites and associated strata

The authors completed two closely spaced transects (separated by < 1km) throughout the supra-olistostrome succession in 2015. The thickest (and southernmost) of these is incorporated into our representative stratigraphic column (**Fig. 2**) and has been presented in detail as **Fig. 5**. A similarly detailed (northern) section was completed for comparative purposes, and an attempt to correlate these two sections is made herein (**Fig. 9**). In many cases, beds and bedsets can be traced out on foot along strike. On the correlation, an obvious thick conglomeratic package (commencing at about 275 m) is immediately overlain by the upper diamictite in both logs. The basal contact of this conglomerate package is undulatory in character, cutting down into underlying beds to produce a relief of at least 5 m. It is dominated by (i) abundant large boulders (>1 m diameter) and (ii) a wide variety of lithologies (psammite, dolostone, metabasite, oncolitic dolostone, stromatolitic dolostone, sandstone, quartzite and schist). Below the thick conglomerate package, possible channel geometries are apparent between the interbedded heterolithics and pebble to boulder conglomerate facies associations, pinching out from log 1 to log 2 (**Fig. 9**), and toplap and truncation occurs beneath at least one of these conglomeratic bedsets.

Diamictites at the top of the KPF in the northern and central Kingston Range (KP4 of Prave, 1999) are well established (e.g. Mrofka, 2010; Mrofka et al., 2011; Macdonald et al., 2013), though comparatively little described. Occurrences of conglomerate within the upper diamictite package are identical in motif to their counterparts below the thick conglomerate package (typically exhibiting normal grading) but are encased above and below by the diamictite facies association. The conglomerates form part of repetitive fining upward cycles at the bed scale, with typical upward trends over a bed from massive conglomerate, through diffusely laminated intervals to cross-laminated, medium-grained sandstone. Lensoid geometries for the pebble to boulder conglomerate and interbedded heterolithic intervals are observed, and in at least one case (437 m, log 1) lateral transition from conglomerate to heterolithic deposits can be demonstrated.

5. The Kingston Range Fan

Le Heron et al. (2014) and Le Heron and Busfield, 2016) proposed that the supra-olistostrome succession accumulated in a basin that was dominated by turbidite and debrite delivery. The occurrence of dropstones both in fine-grained facies toward the base of the supra-olistostrome succession and in diamictites at its top, testifies to a strong glacial influence (and possibly control upon) stratigraphic architecture. Here, we propose that the overall coarsening upward profile of the supra-olistrome succession corresponds to the progradation of a sand-rich subaqueous fan as defined by Reading and Richards (1994) and which we term the Kingston Range Fan.

The stacked coarsening upward cycles >50 m thick are interpreted as stacked fan lobes, with the abrupt transition into mudrocks at the top of these cycles representing local fan lobe or fan lobe element abandonment (Macdonald et al., 2011; Pyles et al., 2014). The intercalation of graded conglomerates, with thick and continuous sections of the sheet heterolithics facies association, testifies to the development of a fan that dominantly accumulated via a spectrum of high to low density turbidity currents. The thick conglomeratic package with internal scours immediately below the upper diamictite is interpreted as a series of proximal stacked channels deposited by high density turbidites. Even if the recognition of individual fan lobes is not always clear cut (Prélat and Hodgson, 2013), the stratigraphic position of the thick conglomerate package on top of a well expressed, >400 m thick coarsening upward succession shows clear comparison to ancient outcrop examples of submarine fans in Ireland (Pyles et al., 2014).

Interestingly, the lonestone bearing facies association- toward the base of the fan as described by Le Heron and Busfield (2016)- does not occur in the upper part of the fan (upper 350 m of the KPF). Nevertheless, its presence implies the (re)establishment of a glacial influence on deposition early on in fan development, as recorded in comparatively distal turbidites with dropstones. We posit that the stratified diamictite may be the proximal equivalent of the dropstone-bearing heterolithics of the lonestone facies association, thus explaining (i) the upsection disappearance of the lonestone-bearing facies associations to be replaced by (ii) the upper diamictite at the top of the fan.

It is proposed that the upper diamictite is genetically related to underlying deposits, thus demonstrating that the Kingston Range Fan developed either in response to, or under the influence of, re-advancing ice masses. The intercalation of the diamictites with turbidites highlights the genetic connection. Based on this, we do not strongly endorse the idea that in the Southern Kingston Range, and perhaps throughout the eastern Death Valley area more generally, unit KP3 represents the upper part of a Sturtian signal, and the unit KP4 (=upper diamictite of this study) represents a Marinoan glacial phase (see Macdonald et al., 2013). The only possible candidate for an unconformity- an undulating contact of the boulder conglomerate package just below the upper diamictite (**Fig. 9**) **-** is interpreted as a series of proximal stacked channels on the upper part (i.e. proximal reaches) of the Kingston Range Fan. The reappearance of turbidite beds immediately above the boulder conglomerate package (**Fig. 7** B, C) underscores its relationship to the fan system beneath: once the boulder conglomerate package was emplaced, normal sedimentation conditions resumed, culminating in deposition of the upper diamictite.

In summary, based upon our field observations in the thickest succession of the KPF, we propose that there is a genetic connection between the supra-olistostrome complex and the upper diamictite, in the eastern Death Valley area. This interpretation contrasts with previous views that the upper diamictite (KP4 of Prave, 1999) represents the deposits of a separate, possibly Marinoan glaciation, as argued by Macdonald et al. (2013). It should be appreciated that absolute age constraints on the KPF remain poor. Assuming that the C isotope profile in the Noonday Dolomite faithfully records a post-Marinoan signal (Prave, 1999), our observations to not discount the possibility that the Kingston Range had become a palaeohigh during the Marinoan glaciation, with no sediments being deposited. This study therefore shows that detailed sedimentological observations have an important role to play in the establishment of regional stratigraphic frameworks in the Neoproterozoic of the Death Valley area, and across the Cordillera more generally. The recognition of a 2.5 km thick succession that has a much more complete sedimentary record than previously assumed, is also important in the context of the global search for a Cryogenian Global Stratotype Section and Point (GSSP) (Condon et al., 2015).

6. Representativeness, completeness, and sequence stratigraphy

In the southern Kingston Range, the thickest hitherto described section of the Kingston Peak Formation raises questions about representativeness and completeness of Cryogenian glacial strata. In the recent paper, Le Heron et al. (2017) presented new data from the Silurian Hills- approximately 30 km west of the study area in the present paper- arguing, for the first time, that clear evidence of glacial processes could be identified within the rock record. There, previous workers (Basse, 1978) had proposed the occurrence of a major subaqueous fan complex built from debrites and turbidites that resemble the strata in the supra-olistostrome complex in the southern Kingston Range. Those diamictites, and associated dropstone-bearing heterolithics, were dominated by basement-derived clasts (including gneiss, schist, granitoid and quartzite).

In a similar manner to the Kingston Range succession, megaclasts of carbonate were also recognised, and interpreted as up to four intercalated olistostrome deposits. Le Heron et al. (2017) pointed out the problems with establishing the significance of the multiple stratigraphic occurrences of glacial diamictites in the Silurian Hills: do they represent multiple phases of glacially sourced debrites from an ice margin during a single glacial cycle, or do they represent multiple phases of advance and retreat? Considering the 1.4 km of KPF stratigraphy in the Silurian Hills, the 2.5 km of KPF stratigraphy in the southern Kingston Range, and the c. 1 km stratigraphy in the Panamint Range (see Miller, 1985; Prave, 1999; Petterson et al., 2011), an abiding problem is in determining which of these differing, undated sections should be regarded as the definitive Death Valley glacial record.

Much significance is placed on the “well-developed nonglacial stratigraphy” in the Panamint Range (Macdonald et al., 2013, p. 1205), which includes a carbonate interval (the Sourdough limestone). With the Sourdough limestone interpreted as a Sturtian cap carbonate passing up into an interglacial / nonglacial stratigraphy, and the overlying Wildrose Diamictite interpreted as a Marinoan glacial deposit (Prave, 1999; Petterson et al., 2011), it is clear to see how this thinking has developed. Nevertheless, based on new work in the Silurian Hills, we argue that a healthy degree of scepticism should be maintained. There, new U-Pb apatite geochronology from metabasite bodies in the KPF yield 1.1 Ga dates (Vandyk et al., in review). These were previous interpreted as diabase sills, because the metabasite bodies are bedding concordant and occur at multiple stratigraphic intervals. Close and careful examination, however, reveals that the metabasites become disaggregated along strike, with rounded boulders of the same metabasite material encased in glacial diamictite. Noting these field relationships, the unexpectedly old U-Pb dates, and the geochemical similarity to diabase sills in the underlying Crystal Spring Formation, Vandyk et al. (in review) proposed that the diabase "sills" in the KPF were better interpreted as olistoliths. These authors also recommended that given some geochemical similarities between the Silurian Hills metabasites and so-called MORB pillow lavas in the Surprise Member of the KPF in the Panamints (Hammond, 1983), their stratigraphic context should be rescrutinized (i.e. whether they are *in situ* extrusives or whether they are also olistoliths). Similarly, given the km-size of carbonate olistoliths across the Death Valley area (e.g. Walker et al., 1986; Prave, 1999; Calzia et al., 2000; Macdonald et al., 2013; Le Heron et al., 2014; Le Heron et al., 2017), care must be taken to ensure that carbonate intervals are really *in situ* beds and do not represent olistoliths.

The above considerations suggest that the identification of a representative or idealised glacial stratigraphy for the KPF over the Death Valley area is still premature. However, based upon our comparative southern Kingston Range sections (**Fig. 9**), we propose a sequence stratigraphic interpretation that follows the methodology of Powell and Cooper (2002), and which has successfully been applied to Sturtian glacial strata in South Australia (Busfield and Le Heron, 2014). This methodology can be used to unravel the nature of glacial cycles, and by comparison to other outcrop belts, potentially enable common stratigraphic patterns to be recognised. Based upon the stacking patterns of bedsets, we identify some well-defined, progradational parasequence sets which collectively represent ice minima, advance, retreat, and maximum systems tracts (**Fig. 9**). Some stratigraphic surfaces are associated with truncation of underlying strata (e.g. glacial advance surface) whereas other stratigraphic contacts (e.g. the glacial erosion surface) superpose the upper diamictite succession on underlying heterolithics (**Fig. 9**). At the local scale, given the close spacing between the detailed sections, (i) a case for ~50 m thick channels can be made and (ii) toplap and truncation of beds beneath the glacial advance surface is notable. Collectively, these phenomena testify to considerable lateral inhomogeneity within the succession at the local scale. At the regional scale, they challenge us to consider which of the thick Death Valley KPF successions is most representative of this formation at the local scale. In addition to the clear role of tectonics superimposed on glaciation or vice-versa, this also applied to the fine-grained record (e.g. shaley intervals in turbidites of the Kingston Range Fan): Trabucho-Alexandre (2015) has argued that even for basinal shales there is more gap than stratigraphic record. More widely, and at a global scale, we are challenged to consider which of the thick Death Valley successions record the global signature of Sturtian glaciations, if there is indeed a representative signature. These uncomfortable questions need to be addressed and overcome in the search for a suitable Cryogenian GSSP.

7. Conclusions

- A complete, detailed section through the KPF in the southern Kingston Range is presented for the first time. The true thickness measures 2.5 km, and represents the thickest and arguably most complete section of this formation in the Death Valley area. The succession comprises (i) a Basal Diamictite, (ii) an olistostrome complex, including km-scale megablocks, succeeded by (iii) a supra-olistostrome succession some 500 m thick;
- The supra-olistostrome succession includes 4 facies associations. The lowest 170 m is dominated by intercalation of comparatively dilute (low density) turbidites (sheet heterolithics), some of which contain abundant ice-rafted debris (lonestone-bearing strata), and high density turbidites (cobble-to boulder conglomerate facies association). Upsection, conglomerates become increasingly important, lonestone-bearing heterolithics disappear, and a 100 m thick diamictite-dominated interval (the upper diamictite) characterises the upper 100 m of the KPF. The overall coarsening upward profile of the entire supra-olistostrome succession allows us to propose that these rocks represent a subaqueous fan complex known herein as the Kingston Range Fan;
- The intercalation of diamictites with turbidites in the upper diamictite interval demonstrates a genetic relationship between diamictites and the Kingston Range Fan. Gradation between stratified and massive diamictites (the former bearing dropstone textures) suggests that the stratified diamictites were deposited directly through ice

rafting whereas the massive diamictites represent sediments reworked by debris flows. The stratified diamictites are also posited to be proximal equivalents to the lonestone-bearing facies association. Thus, there is no reason to argue that the upper diamictite is the deposit of a separate glaciation from the remainder of the Kingston Range Fan based on field relationships.

- Sequence stratigraphic analysis of the KPF identifies multiple systems tracts allied to glacial advance, maxima, retreat and minima conditions in the southern Kingston Range. Internal stratigraphic breaks are recognised that include glacial advance surfaces, and a glacial erosion surface at the ice maxima. The former surface truncates underlying strata which toplap against it, whilst the glacial erosion surfaces superposes diamictite on top of underlying mass flows of the Kingston Range Fan. At the local scale, dramatic lateral facies changes are also recognised, including channels. Collectively, the inhomogeneity of the succession underscores the difficulty in choosing the most characteristic Cryogenian succession, either as a faithful representative of the KPF in Death Valley, or in a more global context as a Cryogenian GSSP.

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FIGURE CAPTIONS

Figure. 1: Geological sketch map and location of sedimentary logs, samples, and photographs in this paper, modified from Le Heron and Busfield (2016). A: Overview of the Death Valley area, showing the location of the major mountain ranges that expose Neoproterozoic strata. B: Geological sketch map of the area. Note that the main transects through the succession are shown. The low-resolution and high-resolution transects together allow a sedimentary log throughout the entire KPF to be presented (see Fig. 2). The two high resolution transects through the supra-olistostrome strata includes an upper diamictite unit KP4 of Prave, 1999). Transect (i), as the thickest and most complete of these, is shown on Fig. 5. The sedimentary logs from both transects are compared and correlated on Fig. 9.

Figure. 2: Sedimentary log of the entire KPF exposed in the southern Kingston Range- the thickest succession in the eastern Death Valley area. The authors undertook very detailed measurement of the upper part of the succession (supra-olistostrome deposits) to a resolution of 10 cm. Accurate portrayal of the olistostrome deposits was possible through mapping and spot measurements, dip values, and true thickness restoration. Thus, the internal stratigraphy of the olistostrome deposit is illustrated. The exposure quality of the basal diamictite ("KP2") is very low in the southern Kingston Range, so textural comparisons with the upper ("KP4") necessarily rely on observations made several kilometres north at 35°44.810N, 115°51.612W.

Figure. 3: Panoramic view (A= true scale; A'= 3 X vertical exaggeration) of the Kingston Peak Formation in the southern Kingston Range from the lowermost strata (basal diamictite), through the olistostrome complex (commencing in this location with a >500 m thick dolostone block), the intercalated metabasites and turbidites, to the supra-olistostrome succession represented by brownish weathering slopes toward the centre of the panoramic. The panoramic spans about 110° from the left (NW) to right (E) of the image.

Figure. 4: Aspects of the olistostrome complex in the southern Kingston Range. A: Boudinaged strata in the lowermost part of the olistostrome, immediately beneath the >500 m thick dolostone megablock. B: Small-scale folds beneath boudinaged strata shown in A. Images C-H show crystalline metabasites and associated sedimentary strata. C: Metabasite and quartzite clasts sitting within a metabasite groundmass. D: Highly irregularly shaped boulder of dolostone encased within metabasite groundmass. E: Pebble-sized clast of metabasite in groundmass of the same composition, with subtle clast boundaries. F: Thin section image of the metabasite, illustrating extensive chlorite replacement of feldspar. G: Stratigraphic contact between metabasite and overlying siliciclastic sedimentary rocks: concordant and conformable. H: Interference-rippled surface on a normally graded sandstone sandwiched between metabasite deposits.

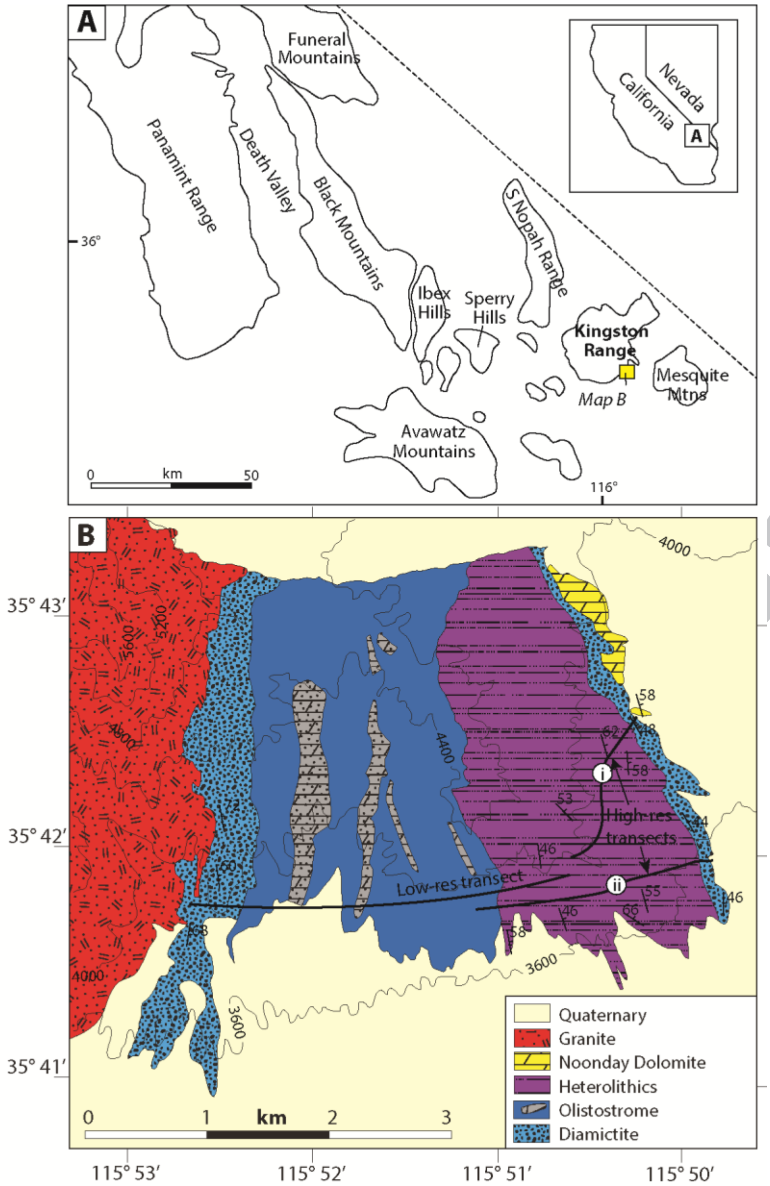
Figure. 5: Detailed logged section throughout more than 600 m of stratigraphy in the supra-olistostrome interval in the southern Kingston Range. This detailed transect includes data from two field seasons in 2014 and 2015. The lowest 170 m were logged in detail by Le Heron and Busfield in 2014 (published in Le Heron and Busfield, 2016), with particular focus on the distribution of ice-rafted debris. The overlying 430 m were logged in 2015, by Le Heron, Ali and Tofaif, and are described in detail herein. All the data are considered in the context of regional ice sheet dynamics in this paper, with particular focus on the context and global significance of the diamictite facies association, commencing at 510 m. This has previously been regarded as “Marinoan” in age, and genetically distinct as a unit from the underlying strata (Macdonald et al., 2013).

Figure. 6: Diamictite lithofacies and stratigraphic contacts toward the top of the Kingston Peak Formation. A: Vertical transition from massive, through stratified diamictite, passing up into sandstone above the hammer handle. B: Cobble-sized dropstone (to the left of the hammer) in stratified diamictite. Note graded sandstone beds above. C: Striated surface on a sandstone clast embedded in massive diamictite. D and E: Small pebble-sized dolostone clasts in stratified diamictites. In each case, laminations are punctured beneath the clasts. F: Upper contact between stratified diamictites of the Kingston Peak Formation and the Noonday Dolomite. Strata are dipping at about 45°, and the base of the Noonday is a low angle, but demonstrably angular, unconformity. Whilst the contact between the formations appears conformable at a local scale, tracing the contact for a few hundred metres along strike provides evidence for truncation of diamictite beds.

Figure. 7: Features diagnostic of turbidites in the uppermost part of the Kingston Peak Formation. A: Asymmetric ripples on the surface of a sandstone bed, indicative of a palaeoflow moving in the direction implied by the arrow (i.e. toward the SE). B: Relationship between rippled surface shown in A and overlying deposits. The rippled sandstone surface is directly overlain by highly recessive mudstone (covered in vegetation) and then a graded bed on which the hammer is placed. C: orthogonal view of the graded bed shown in B. Note the clear vertical transition from clast-supported conglomerate to reddish-brown sandstone. D: Relationship between diamictite and normally graded conglomerate: transitional. E: Repetitively stacked graded beds, interrupted by a massive diamictite bed. Note the concordant though slightly irregular contact. F: Detail of unidirectional cross-lamination toward the top of one of the sandstone beds shown in E.

Figure. 8: Textures and composition of the upper diamictites of the Kingston Peak Formation. A and B: Ferric and ferrous variants of stratified diamictite. C to H: examples of pebble-sized clasts. C and D show predominantly dolostone clasts, though D shows a metamorphosed sandstone clast (psammite). E and F show finely crystalline and coarsely crystalline variants of a metabasite that has identical weathering properties to the metabasites in the olistostrome complex. The clasts are thus considered to be locally sourced. G: Oncolitic dolostone, possibly derived from the Beck Spring Formation. H: sandstone and quartzite clasts.

Figure. 9: Two closely spaced sedimentary logs through the uppermost part of the Kingston Peak Formation (2015 traverse), with an attempted correlation between them. The upper 430 m of Fig. 3 corresponds to the log shown on the left. Note evidence for (a) impressive lateral thinning of conglomerates between 110-155 m on log I and log ii; (b) possible truncation and toplap at 225 m; (c) internal heterogeneity within the upper diamictite. A sequence stratigraphic analysis, based on the methodology of Powell and Cooper (2002) and successful applied elsewhere to Cryogenian diamictite successions (Busfield and Le Heron, 2014) is shown to the right of the sections.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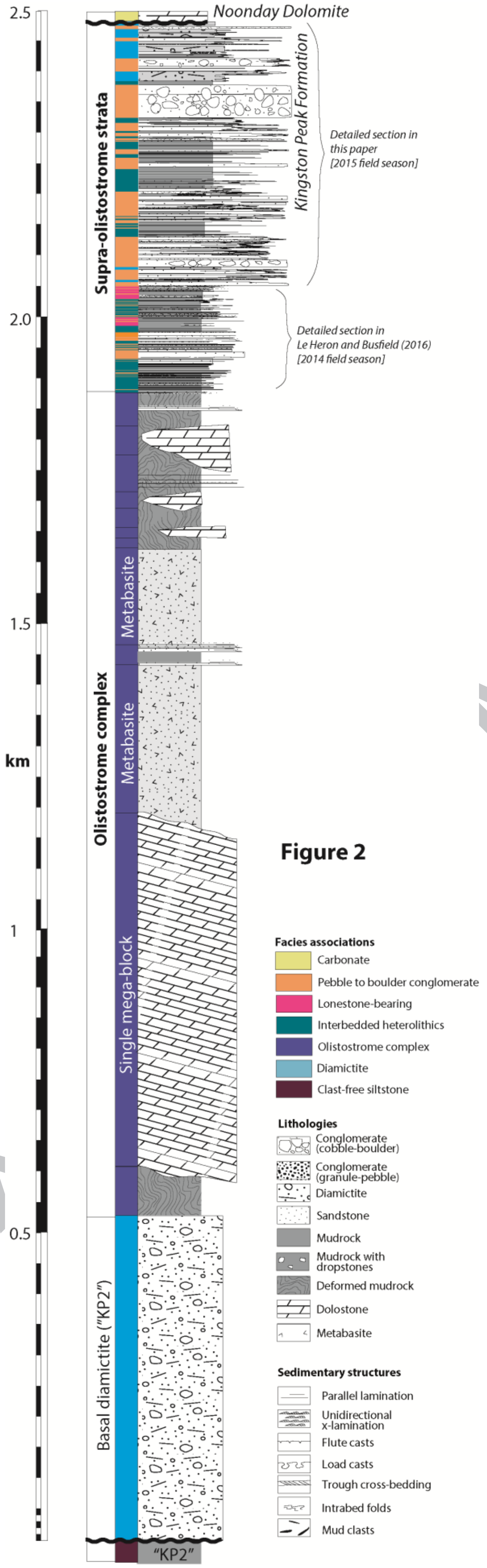

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Kingston Peak Formation
Detailed section in this paper [2015 field season]
Detailed section in Le Heron and Busfield (2016) [2014 field season]
Supra-olistostrome strata
Olistostrome complex
Metabasite
Metabasite
Single mega-block
Basal diamictite ("KP2")
"KP2"
Facies associations
Carbonate
Pebble to boulder conglomerate
Lonestone-bearing
Interbedded heterolithics
Olistostrome complex
Diamictite
Clast-free siltstone
Lithologies
Conglomerate (cobble-boulder)
Conglomerate (granule-pebble)
Diamictite
Sandstone
Mudrock
Mudrock with dropstones
Deformed mudrock
Dolostone
Metabasite
Sedimentary structures
Parallel lamination
Unidirectional x-lamination
Flute casts
Load casts
Trough cross-bedding
Intrabed folds
Mud clasts

Figure 2

774

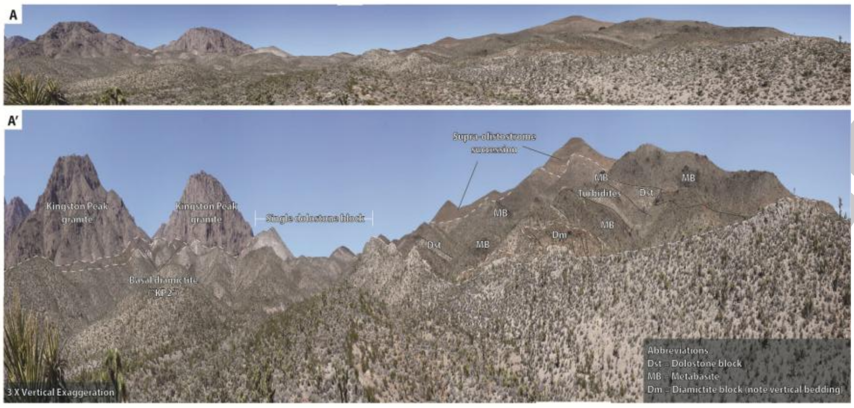

A
A′
Kingston Peak granite
Kingston Peak granite
Single dolostone block
Supra-olistostrome succession
MB
MB
Turbidites
Dst
MB
MB
Dst
MB
Dm
Basal diamictite "KP2"
3 X Vertical Exaggeration
Abbreviations
Dst = Dolostone block
MB = Metabasite
Dm = Diamictite block (note vertical bedding)

Figure 3

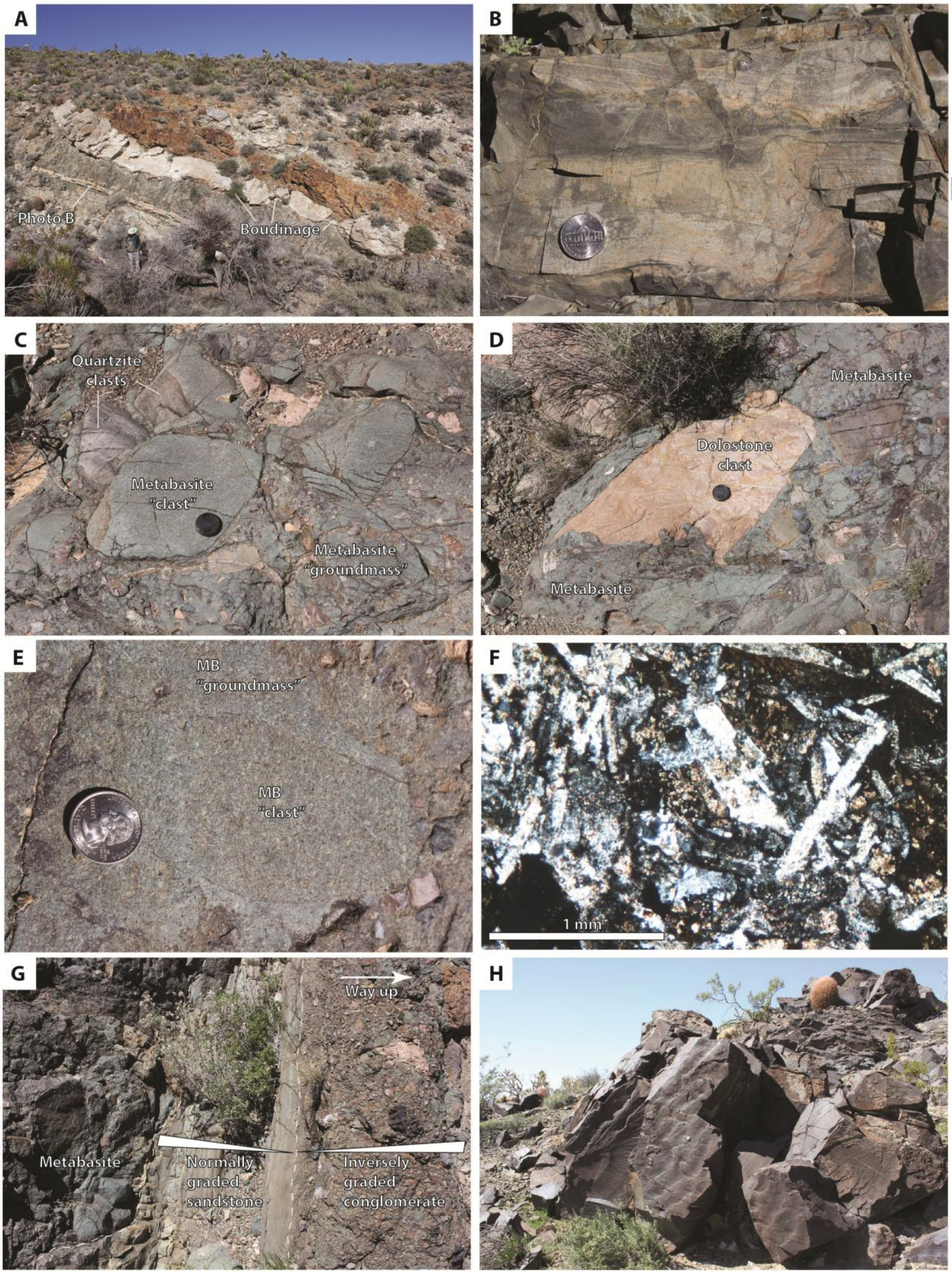

A
Photo B
Boudinage
B
C
Quartzite clasts
Metabasite "clast"
Metabasite "groundmass"
D
Metabasite
Dolostone clast
Metabasite
E
MB "groundmass"
MB "clast"
F
1 mm
G
Way up
Metabasite
Normally graded sandstone
Inversely graded conglomerate
H

Figure 4

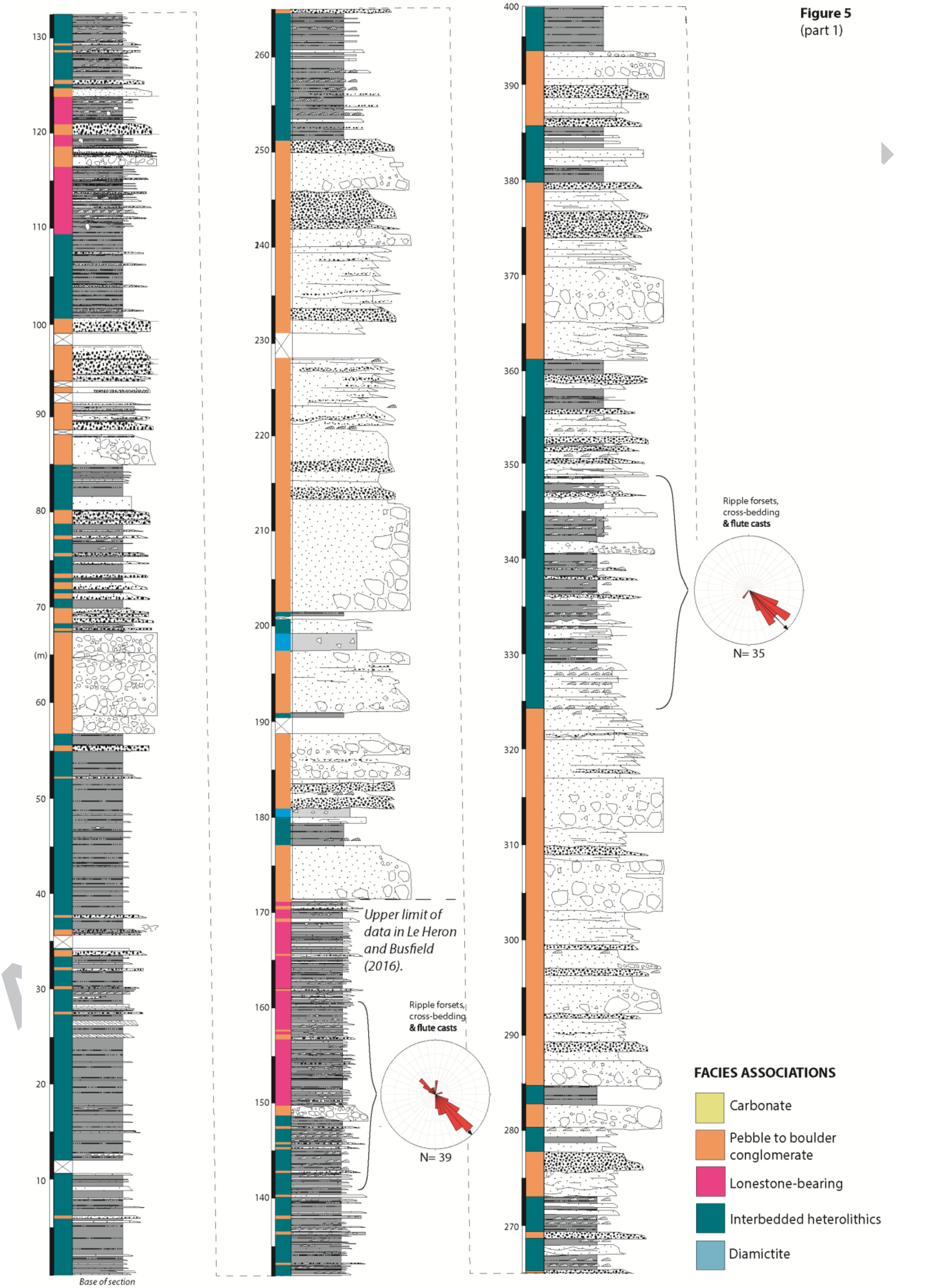


Figure 5
(part 1)
Base of section
(m)
Upper limit of data in Le Heron and Busfield (2016).
Ripple forsets, cross-bedding & flute casts
N= 39
Ripple forsets, cross-bedding & flute casts
N= 35
FACIES ASSOCIATIONS
Carbonate
Pebble to boulder conglomerate
Lonestone-bearing
Interbedded heterolithics
Diamictite

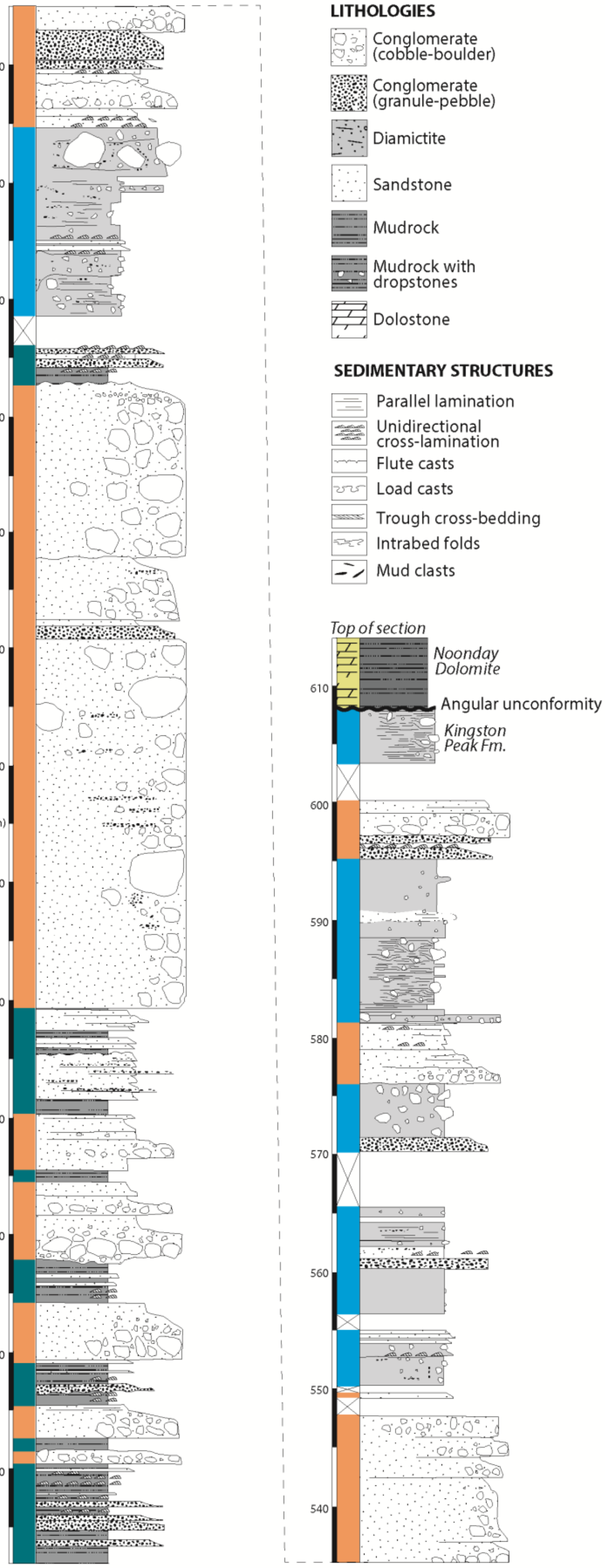


Figure 5
(part 2)

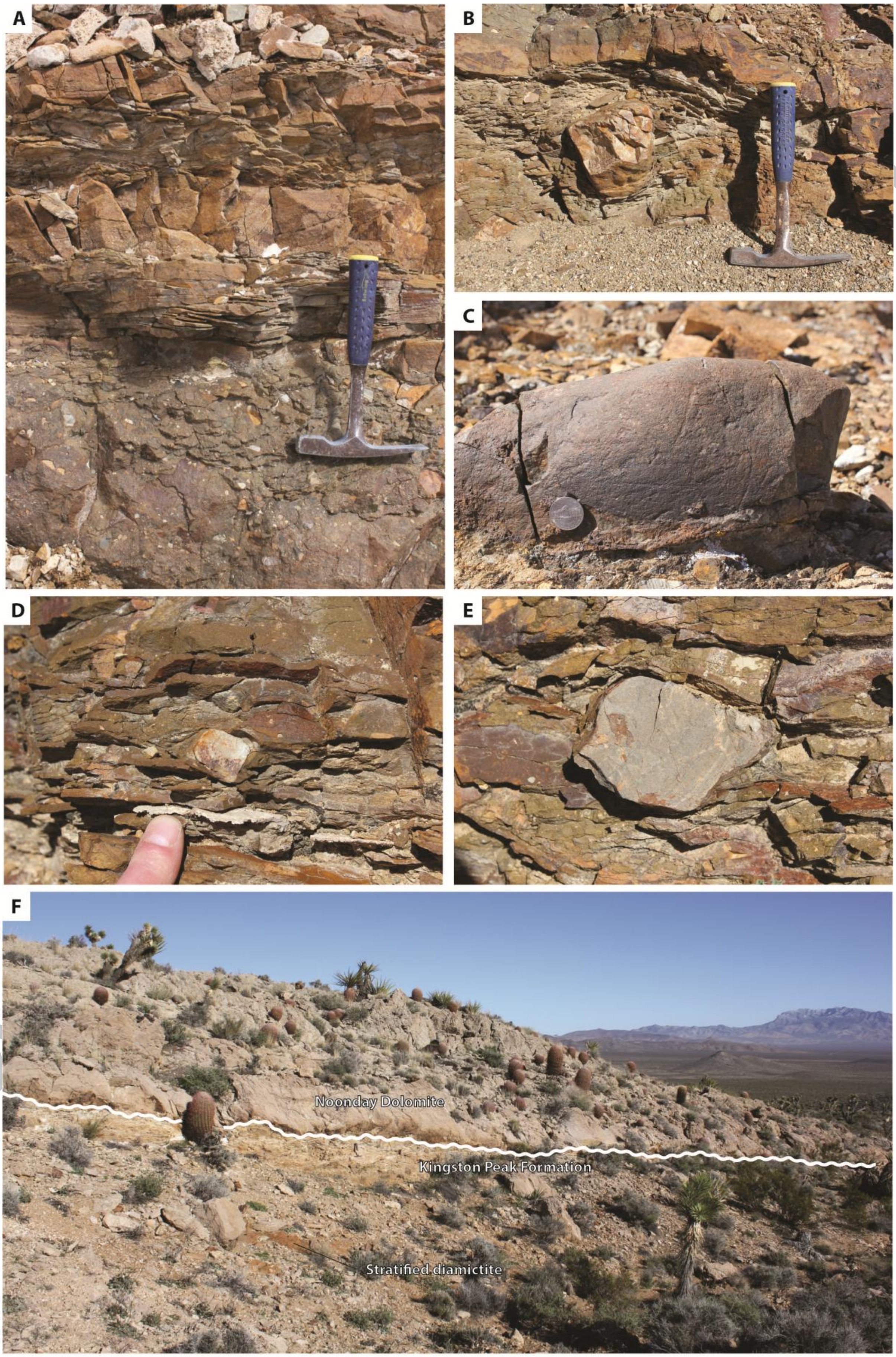

A
B
C
D
E
F
Noonday Dolomite
Kingston Peak Formation
Stratified diamictite

Figure 6

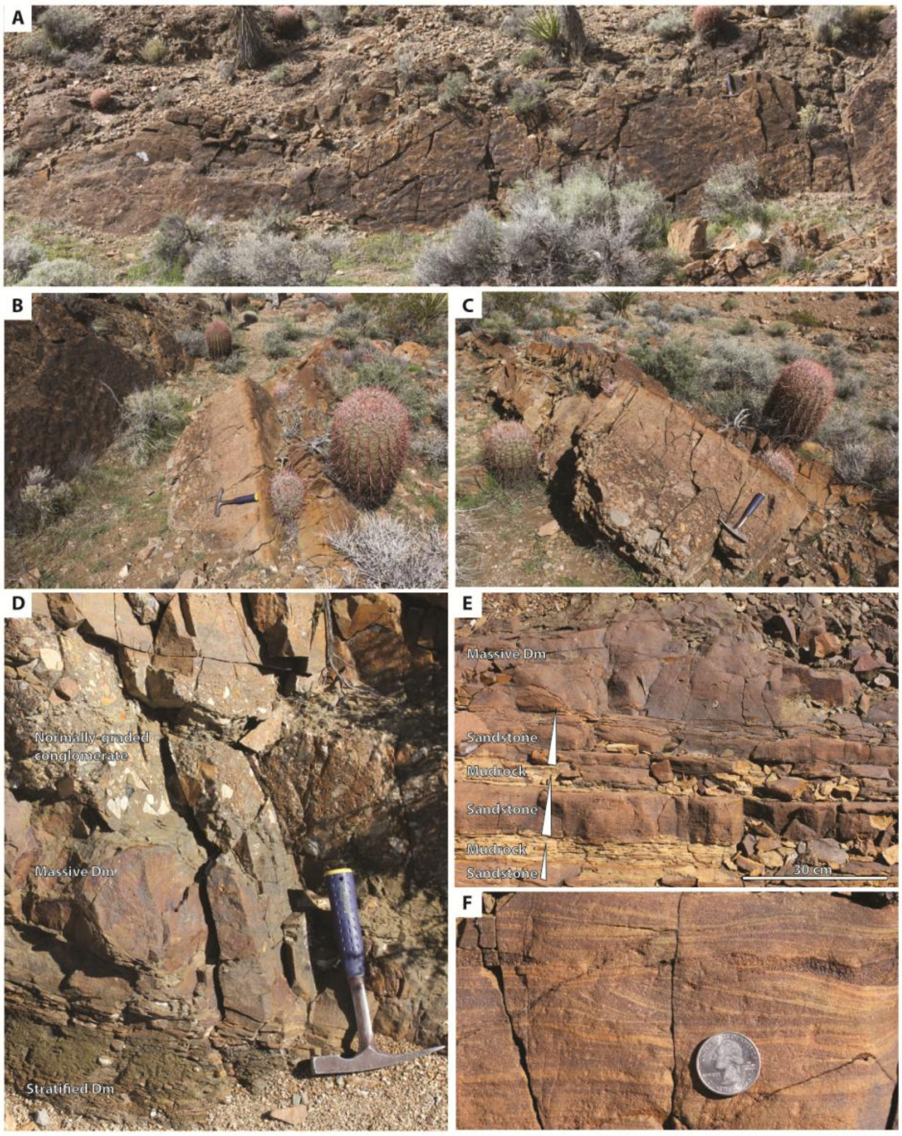

A
B
C
D
Normally-graded conglomerate
Massive Dm
Stratified Dm
E
Massive Dm
Sandstone
Mudrock
Sandstone
Mudrock
Sandstone
30 cm
F

Figure 7

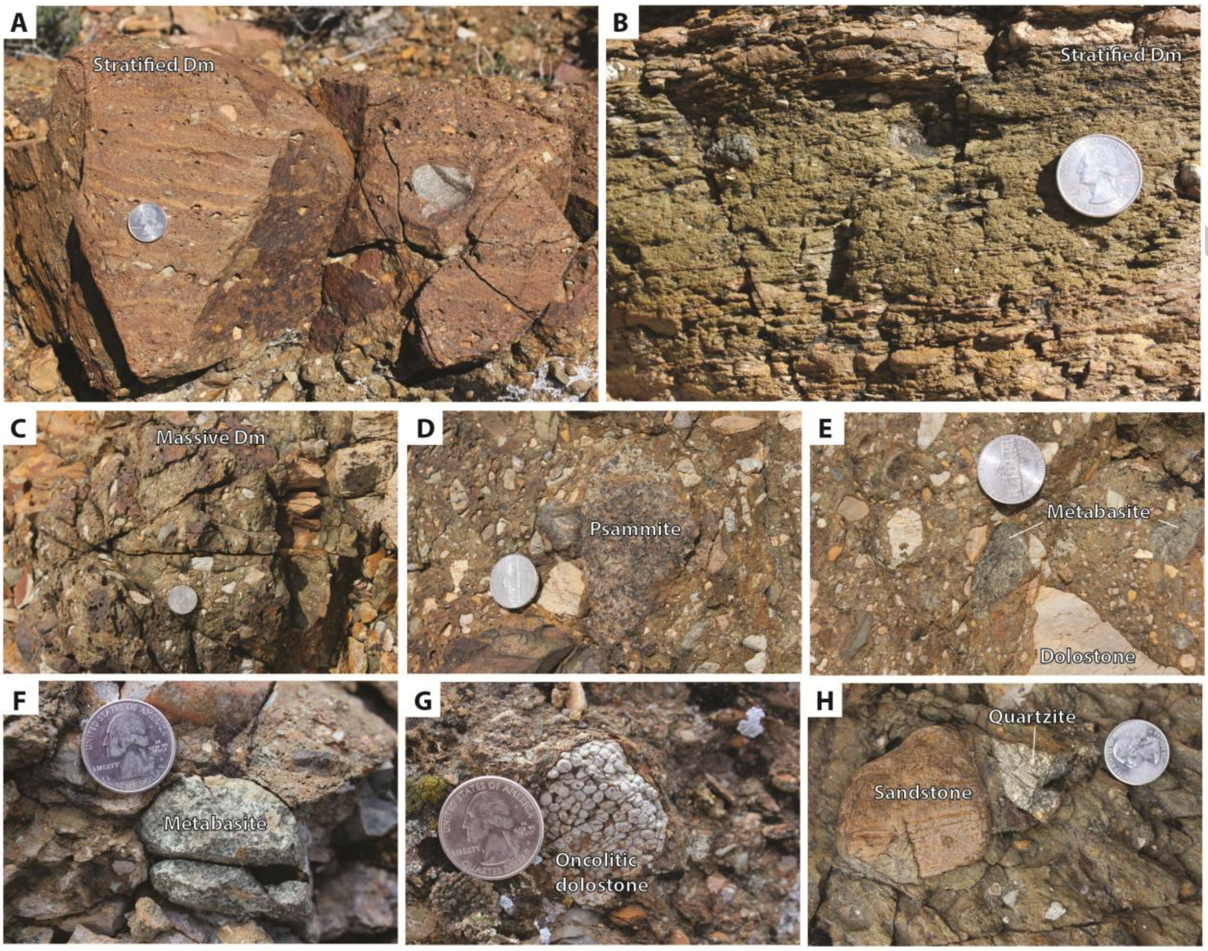
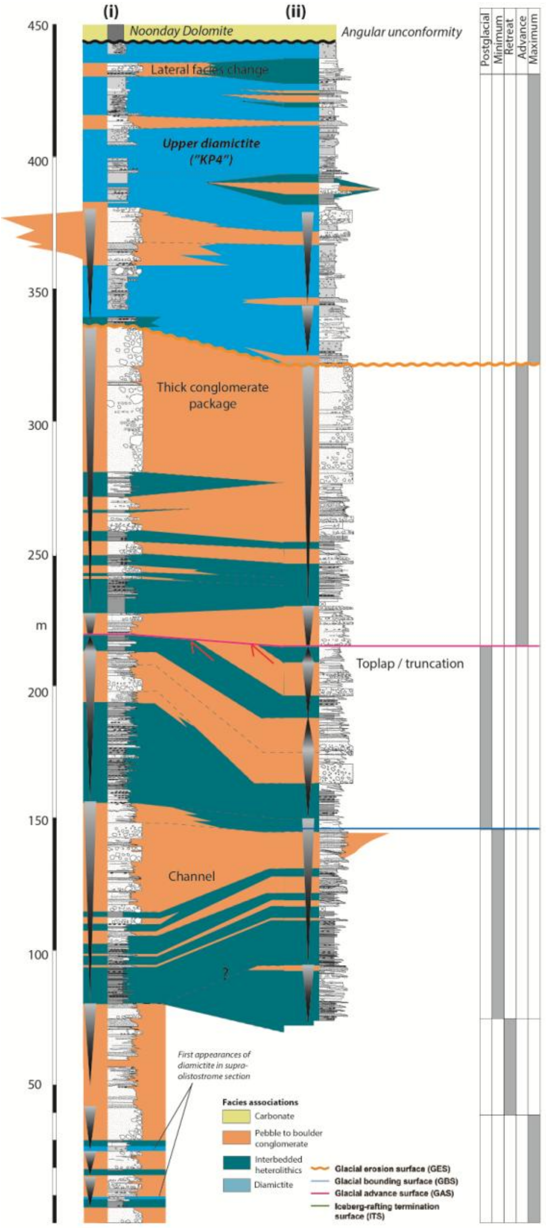

A
Stratified Dm
B
Stratified Dm
C
Massive Dm
D
Psammite
E
Metabasite
Dolostone
F
Metabasite
G
Oncolitic
dolostone
H
Quartzite
Sandstone

Figure 8



(i)
(ii)
450
400
350
300
250
m
200
150
100
50
Noonday Dolomite
Angular unconformity
Lateral facies change
Upper diamictite
("KP4")
Thick conglomerate
package
Toplap / truncation
Channel
?
First appearances of
diamictite in supra-
olistostrome section
Facies associations
Carbonate
Pebble to boulder
conglomerate
Interbedded
heterolithics
Diamictite
Glacial erosion surface (GES)
Glacial bounding surface (GBS)
Glacial advance surface (GAS)
Iceberg-rafting termination
surface (ITS)
Postglacial
Minimum
Retreat
Advance
Maximum

Figure 9

Highlights

- The sedimentology of the thickest succession of Cryogenian glacially-related strata in the Death Valley area- the Kingston Peak Formation (KPF)- is described in detail for the first time from the southern Kingston Range. The KPF is important as one of Laurentia's finest archives of Cryogenian glaciation, with the outcrop quality meriting consideration as a potential GSSP.
- In the southern Kingston Range, strata represent a major subaqueous fan complex that was deposited under the competing influence of rifting and glaciation.
- A sequence stratigraphic interpretation suggests that discrete phases of glacial advance, retreat, glacial maxima and glacial minima is proposed, which is useful to understand ice dynamics at a local scale.
- Uncertainty surrounds the stratigraphic value of many KPF subdivisions that have been previously proposed. This re-opens questions about representativeness and completeness of the Death Valley record.